Application of Bimodal Master Curve Approach on KSNP RPV steel SA508 Gr. 3

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1. Introduction

The basic master curve (MC) method was proposed by Wallin, which was adopted in the ASTM E1921 [1-3]. The MC approach can be used to predict the brittle fracture behavior for macroscopically homogeneous steels only with a bcc structure, including ferritic and tempered ferritic-martensitic steels. However, the material is not homogeneous in reality. Such inhomogeneity comes in the effect of material inhomogeneity depending on the specimen location, heat treatment, and whole manufacturing process. The conventional master curve has a limitation to be applied to a large scatted data of fracture toughness such as the weld region. To overcome these limitations of a conventional MC approach, a SINTAP lower tail analysis procedure, BMC (Bimodal Master Curve), and RIMC (Randomly Inhomogeneous Master Curve) are introduced [4]. In this paper, the standard MC approach and BMC are applied to the forging material of the KSNP RPV steel SA508 Gr. 3. A series of fracture toughness tests were conducted in the DBTT transition region, and fracture toughness specimens were extracted from four regions, i.e., the surface, 1/8T, 1/4T and 1/2T. Deterministic material inhomogeneity was reviewed through a conventional MC approach and the random inhomogeneity was evaluated by BMC.

2. Fracture Toughness Evaluation

2.1 Material and specimens

The materials investigated are KSNP RPV base metals SA508 Gr. 3. Fig. 1 shows the investigated RPV block, which was divided into several plates from the inner surface using a wire travelling electroerosive discharging machine. The specimens were extracted at the locations of the surface, 1/8T, 1/4T and 1/2T. Fracture toughness tests were conducted over a temperature range of -150 to -80°C with Pre-cracked Charpy V-Notch (PCVN) 3-point bend specimens (10 mm × 10 mm × 55 mm), in which the initial fatigue crack length-to-width ratio was about 0.5. Yield strength can be expressed as a function of temperature in the range of -196°C to room temperature using the exponential relationship as follows:

$$\sigma_{YS}=450.74+32.83\,exp\left(-\frac{T}{73.14}\right) \qquad (1)$$

2.2 Deterministic Material Inhomogeneity

Table 1: Standard master curve reference temperature T_0 at each location

Location	Number of specimens	T_0 (°C)
Surface	29	-131.7
1/8T	25	-116.1
1/4T	23	-103.9
1/2T	23	-96.2

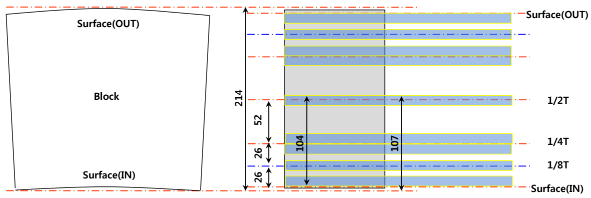

Fig. 1. Investigated RPV block and locations of specimen extraction.

The K_{JC} values were ordered to investigate the deterministic inhomogeneity by the thickness location. Table 1 shows the dependence of the standard MC reference temperature T_0 on the sampling location of the plates of the base metal. T_0 increases from the inner surface to the 1/2T thickness location of the forging as expected. There is a clear tendency for T_0 to have a low value owing to the higher quenching rate at the surface.

Fig. 2 shows a comparison between the standard MC using specimens located in the middle region from 1/4T to 1/2T and that using specimens located in all regions from the surface to 1/2T. The solid lines correspond to the MC using the middle region datasets, and the dotted lines correspond to the MC using all region datasets. The lower and upper bound curves of MC using the 1/4T and 1/2T datasets covered most of the datasets with some outliner. This also means that random inhomogeneity effect exists. The T_0 reference temperature, -100.2°C, determined by datasets of the center region (1/2T+1/4T), is similar to the T_0 reference temperature determined by each data set of 1/4T(T_0=-103.9°C) and 1/2T(T_0=-96.2°C) regions. If data of all regions are treated as one single region (dotted line), as shown in Fig. 2, the upper bound curve covered the high K_{JC} values and T_0 decreases to -116°C while more data lie below the lower bound curve because the K_{JC} values of the surface and 1/8T are relatively higher than those of the center region. Namely, the standard MC and T_0 (-100.2°C) using the center region data representing the solid line in Fig. 2 give a similar result with T_0 (-103.9°C) of the 1/4T region in Table 1. Based on the comparison of T_0, the conventional MC method predict well from the RPV evaluation point of view in which 1/4T data are used for the assessment of RPV integrity.

When the deterministic inhomogeneity effect due to the extraction location and quenching rate is treated as random inhomogeneity effect, T_0 determined by all region datasets is applicable for the simulation of random inhomogeneity. With this assumption, the dotted line in Fig. 2 can be used, and the upper bound curve of MC using datasets of all regions covering higher K_{JC} values, which were outliners when using only the center region datasets. However, a number of K_{JC} values lying below the lower bound curve are increased. From the analysis results, if all datasets are treated as single region datasets to simulate random inhomogeneity, a conventional master curve has a limitation owing to its narrow scatter band. Large scatters mostly come from the deterministic inhomogeneity, but the surface and 1/8T data show the possibility of random inhomogeneity.

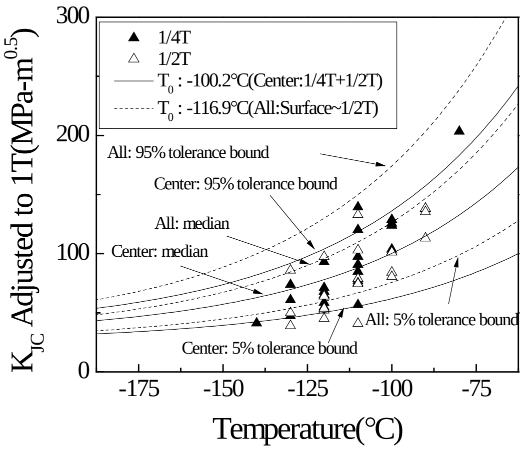

Fig. 2. Standard master curve and measured K_{JC} values at 1/2T and 1/4T

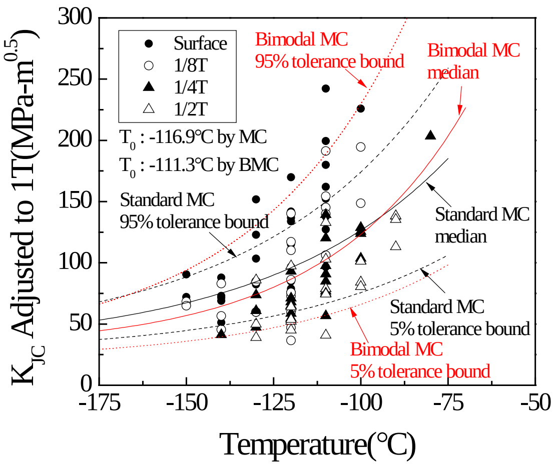

Fig. 3. Standard and bimodal master curve with all measured K_{JC} values

2.3 Bimodal Master Curve Methods

Fig. 3 shows comparisons between conventional MC and bimodal MC for all locations and temperatures. T_0 was -116.9°C by the conventional MC method, and was -111.3°C by the bimodal MC method. Notably, the T_0 values derived by both analyses are similar, and the main difference comes in values of the standard deviation. On the whole, 5% lower bound and 95% upper bound curve of the BMC shown with a dotted red line was a relatively wide range compared with that of a conventional MC. BMC shows good applicability for covering large scatters because they use two fracture toughness distributions. When the deterministic inhomogeneity owing to the extraction location and quenching rate is treated as random inhomogeneity, the bimodal analysis noticeably improves the description of the scatter of fracture toughness data; however, BMC and MC provide almost the same T_0 values. This indicates that the standard MC evaluation method for this material is appropriate even though the standard MC has a narrow upper/lower bound curve range when considering the sample size to evaluate BMC, which needs a large number of datasets.

3. Conclusions

In the present paper, four regions, surface, 1/8T, 1/4T and 1/2T, were considered for the fracture toughness specimens of KSNP (Korean Standard Nuclear Plant) SA508 Gr. 3 steel to provide deterministic material inhomogeneity and review the applicability of BMC. T_0 determined by a conventional MC has a low value owing to the higher quenching rate at the surface as expected. However, more than about 15% of the K_{JC} values lay above the 95% probability curves indexed with the standard MC T_0 at the surface and 1/8T, which implies the existence of inhomogeneity in the material. To review the applicability of the BMC method, the deterministic inhomogeneity owing to the extraction location and quenching rate is treated as random inhomogeneity. Although the lower bound and upper bound curve of the BMC covered more K_{JC} values than that of the conventional MC, there is no significant relationship between the BMC analysis lines and measured K_{JC} values in the higher toughness distribution, and BMC and MC provide almost the same T_0 values.

Therefore, the standard MC evaluation method for this material is appropriate even though the standard MC has a narrow upper/lower bound curve range from the RPV evaluation point of view.

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